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Research Article

Achieving Energy Efficiency in Building Heating and Cooling by Optimising Solar Energy-Based Control

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ABSTRACT

This paper examines the optimisation of control for a building heating and cooling system integrated with solar energy and a heat pump under the climatic conditions of Fergana Region. Solar irradiance $G(t)$, outdoor air temperature $T_a(t)$ and wind speed $v_w(t)$ were included directly in the model as external disturbances. The model combines building thermal dynamics and wind dependence with electricity generation by the photovoltaic (PV) system and temperature-dependent heating and cooling models for the heat pump. The control problem was formulated as a model predictive control (MPC) method using a mathematical model and future weather forecasts; the objective function simultaneously minimised grid electricity use, deviations from the comfort temperature and frequent compressor changes. A representative year was constructed from monthly values obtained from open meteorological data for Fergana. Daily short-wave solar irradiation on a horizontal surface ranges from 2.0 to 8.0 kWh/m²·day, monthly mean air temperature from 0.6 to 28.3 °C, and mean wind speed from 1.48 to 3.17 m/s. For a 150 m² building equipped with a 6 kWp PV system and an 8 kW heat pump, model calculations showed that optimised control reduced the heat pump's annual electricity consumption from 6,007 to 4,578 kWh, a reduction of 23.8%. By aligning PV generation with the load over time, electricity drawn from the grid fell from 3,764 to 1,435 kWh per year.

KEYWORDS



Solar energy; heat pump; building heating and cooling; model predictive control; Fergana; solar irradiance; wind; energy efficiency; PV; HVAC.

1. INTRODUCTION

Building heating and cooling systems are dynamic energy consumers that depend strongly on outdoor meteorological conditions. Outdoor air temperature, solar irradiance, wind, and heat losses through the building envelope vary over hourly and seasonal timescales. Conventional thermostat control therefore often responds only to the current temperature and does not use expected solar energy availability or weather forecasts. Recent literature identifies model predictive control (MPC) as a promising approach to jointly optimising energy use and thermal comfort in building HVAC systems [1–22].

Heat pumps are an important technology for electrified heat supply, and their real-world efficiency depends on outdoor air temperature, condensing and evaporating temperatures, and part-load operation. A solar photovoltaic (PV) system can partially cover heat pump consumption, but the greatest benefit is achieved when PV generation and heating or cooling loads are aligned in time. Studies combining forecast-based control and thermal energy storage show that energy costs, peak power demand and CO₂ emissions can be reduced [4, 5, 8]. Reviews published in 2025–2026 report substantial energy savings from MPC in real buildings, although results vary between studies [6, 7].

The aim of this study is to develop a control-oriented mathematical model and optimisation

algorithm for a building heating and cooling system operating with a reversible heat pump and a PV system, while accounting for the solar irradiance, wind and outdoor air temperature characteristics of Fergana Region. The scientific novelty lies in integrating wind-dependent infiltration, forecasts of solar energy and the temperature-dependent efficiency of the heat pump within an MPC formulation.

2. Characterisation of Climate Parameters in Fergana Region

Open climate data for Fergana city specify its location as 40.384° N, 71.784° E, at an elevation of 580 m [1]. The monthly mean temperature is approximately 0.6 °C in January and rises to 28.3 °C in July. Mean daily short-wave solar irradiation is 2.0 kWh/m²·day in December and reaches 8.0 kWh/m²·day in July. Mean wind speed is 1.5–1.8 m/s in winter and increases to 3.0–3.2 m/s in summer [1]. The annual total of these values corresponds to an average of 1,816 kWh/m²·year of short-wave solar irradiation on a horizontal surface. The NASA POWER methodology indicates that solar parameters are derived from satellite observations and radiative transfer models, while meteorological parameters are obtained from reanalysis and assimilation models [2].

Table 1. Monthly Climate Parameters Adopted in the Model for Fergana

Month	Mean air temperature (°C)	Daily solar irradiation (kWh/m ² ·day)	Wind speed (m/s)
January	0.6	2.3	1.56

Month	Mean air temperature (°C)	Daily solar irradiation (kWh/m ² ·day)	Wind speed (m/s)
February	2.8	3.1	1.83
March	9.4	4.3	2.19
April	16.7	5.6	2.46
May	21.7	6.7	2.68
June	26.1	7.8	2.95
July	28.3	8.0	3.17
August	26.7	7.3	2.95
September	21.1	5.9	2.55
October	13.9	4.0	2.01
November	7.2	2.6	1.61
December	1.7	2.0	1.48

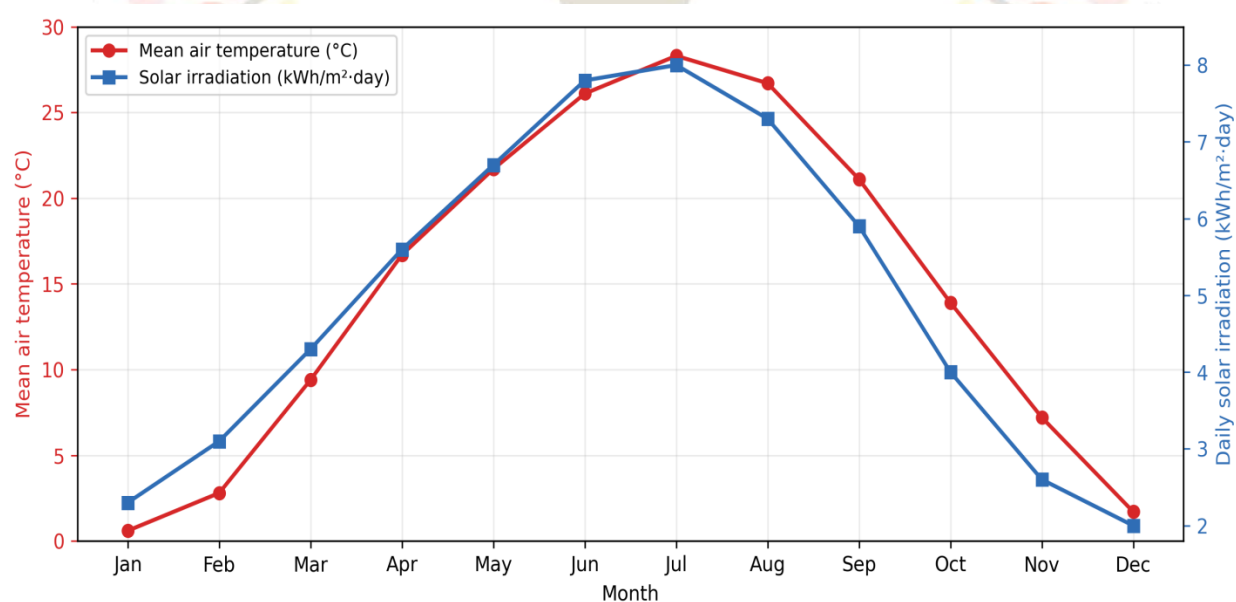


Figure 1. Monthly Mean Air Temperature and Solar Irradiation in Fergana Region.

3. Mathematical Model of the Building, PV and Heat Pump System

3.1. Wind-Dependent Model of Building Heat Losses

The building's overall heat-loss coefficient comprises conductive heat transfer through the envelope and additional losses associated with air infiltration:

$$H_b(t) = U_A + \rho_a c_{p,a} \dot{V}_{inf}(t),$$

$$\dot{V}_{inf}(t) = \dot{V}_0 + k_v v_w(t), \quad (1)$$

where U_A is the overall heat-transfer coefficient through the walls, roof, floor and windows, in kW/K; $\dot{V}_0$ is the baseline infiltration rate; k_v is the wind-sensitivity coefficient; and v_w is wind

speed. An increase in wind speed directly affects the heating load.

The dynamics of indoor building temperature are described by a single-node equation:

$$C_b \frac{dT_i}{dt} = \dot{Q}_{HP} + \dot{Q}_{int} + \dot{Q}_{sol,g} - H_b(t)[T_i - T_a(t)], \quad (2)$$

where C_b is the equivalent thermal capacity of the building; $\dot{Q}_{HP} > 0$ applies in heating mode and $\dot{Q}_{HP} < 0$ in cooling mode; the internal heat source is represented in the model; and $\dot{Q}_{sol,g}$

is passive solar energy transmitted through windows and other glazed elements.

3.2. Solar Photovoltaic System

The hourly electrical power output of the PV system is calculated as follows:

$$P_{PV}(t) = P_{STC} \eta_{der} \frac{G(t)}{1000} [1 + \gamma(T_{cell}(t) - 25)], \quad (3)$$

where P_{STC} is the nominal PV capacity; η_{der} is the derating factor under actual operating conditions; and γ is the PV module temperature

coefficient. Under optimised control, $P_{PV}(t)$ reduces the power drawn by the heat pump from the grid:

$$P_{grid}(t) = \max[P_{HP,el}(t) - P_{PV}(t), 0]. \quad (4)$$

3.3. COP and EER Model of the Reversible Heat Pump

In heating mode, the maximum coefficient of performance, accounting for temperature

dependence, is expressed using the second-law efficiency:

$$COP_h(t) = \eta_{II,h} \frac{T_{cond,K}}{T_{cond,K} - T_{evap,K}(t)}, \quad (5)$$

In cooling mode:

$$EER_c(t) = \eta_{II,c} \frac{T_{evap,K}}{T_{cond,K}(t) - T_{evap,K}}. \quad (6)$$

The electrical power of the heat pump is:

$$P_{HP,el} = \begin{cases} \dot{Q}_{HP} / COP_h, & \dot{Q}_{HP} \geq 0, \\ |\dot{Q}_{HP}| / EER_c, & \dot{Q}_{HP} < 0. \end{cases} \quad (7)$$

This formulation accounts for the decrease in COP during cold winter hours and the deterioration in EER on hot summer days as the condensing temperature rises.

$$x_{k+1} = A_k x_k + B_k u_k + E_k d_k, \quad (8)$$

where $x_k = T_i(k)$; $u_k = \dot{Q}_{HP}(k)$; and the disturbance vector contains forecasts of outdoor air temperature, solar irradiance, wind speed and

4. Control Optimisation Model

For discrete time, Equation (3) is written in state-space form as follows:

$$J = \sum_{j=0}^{N_p-1} \left[w_E P_{grid,k+j} \Delta t + w_T \dot{T}_{T,k+j}^2 + w_{\Delta u} (u_{k+j} - u_{k+j-1})^2 \right], \quad (9)$$

$$\dot{T}_T = \max(T_{min} - T_i, 0) + \max(T_i - T_{max}, 0), \quad (10)$$

subject to the following constraints:

$$T_{min} \leq T_i \leq T_{max}, \quad -Q_{c,max} \leq u_k \leq Q_{h,max}.$$

The first term of the objective function minimises energy drawn from the grid, the second penalises deviations from thermal comfort, and the third minimises abrupt changes in compressor power. When the solar irradiance forecast is high, the controller preheats the building or increases its thermal storage in winter; in summer, it uses pre-cooling during hours of high PV output.

Algorithm 1. Preparing Fergana Climate Data for the Control Model

- Load hourly or monthly time series for T_a , G and v_w .
- Interpolate missing values over time.
- Convert wind speed into an infiltration rate using Equation (2).
- Calculate the PV power forecast from solar irradiance using Equation (4).
- Calculate COP_h and EER_c from Equations (6)–(7) using the outdoor temperature.

internal heat gains. Wind-driven changes in H_b make A_k time-varying.

The MPC objective function over a horizon of N_p is proposed as follows:

- Pass the forecast vector of outdoor temperature, solar irradiance, wind speed and internal heat gains to the MPC.

Algorithm 2. Solar-Adaptive MPC Control

Measure the current $T_i(k)$, $P_{PV}(k)$ and heat pump state.

For the next N_p hours, receive forecasts of T_a , G and v_w .

Solve the constrained optimisation problem in Equations (9)–(12).

Apply only the first $u_{k:k+N_p-1}^*$ from the optimal sequence u_k^* to the system.

After one time step, update the model state using new measurements.

Repeat the process according to the basic operating principle of model predictive control.

Algorithm 3. Seasonal Selection of Heating and Cooling Modes

If the forecast $T_i < T_{min}$, activate heating mode and the COP_h model.

If the forecast $T_i > T_{max}$, activate cooling mode and the EER_c model.

If the temperature is within the comfort range and PV output is low, switch off the compressor.



If PV generation exceeds demand, use the load forecast for the next 3–6 hours and apply preheating or pre-cooling within the permitted comfort limits.

5. Test Case and Numerical Experiment

A single-storey building with a heated floor area of 150 m² was selected as the test case. The model parameters are: C_b=18 kWh/K; a baseline envelope heat-loss coefficient of U_A=0.23 kW/K; an additional wind-sensitive coefficient of 0.025 kW/(K·m/s); internal heat gain of 0.55 kW; PV capacity of 6 kWp; and a reversible heat pump with a maximum thermal capacity of 8 kW. Baseline control maintains a constant setpoint of

22 °C in heating mode and 25 °C in cooling mode. Optimised control uses a comfort range of 20.5–23.0 °C in winter and 23.5–27.0 °C in summer, and shifts the load over time according to the solar forecast.

For the calculations, a 24-hour profile representative of each month was constructed from the monthly values of T_{min}, T_{max} and G_d; these profiles were then multiplied by the number of days in each month to obtain annual estimates. This approach is a simplified computational scenario used in place of a typical meteorological year (TMY). The results should not be interpreted as experimental findings or as the outcome of a certified energy audit.

Table 2. Annual Computational Results for Baseline and Optimised Control

Indicator	Baseline thermostat	Optimised control	Change
Heat pump electricity consumption (kWh/year)	6007	4578	–23.8 %
Electricity drawn from the grid (kWh/year)	3764	1435	–61.9 %
Calculated heating energy (kWh/year)	14859	11392	–23.3 %
Calculated cooling energy (kWh/year)	4944	4174	–15.6 %
Nominal PV capacity	6 kWp	6 kWp	unchanged

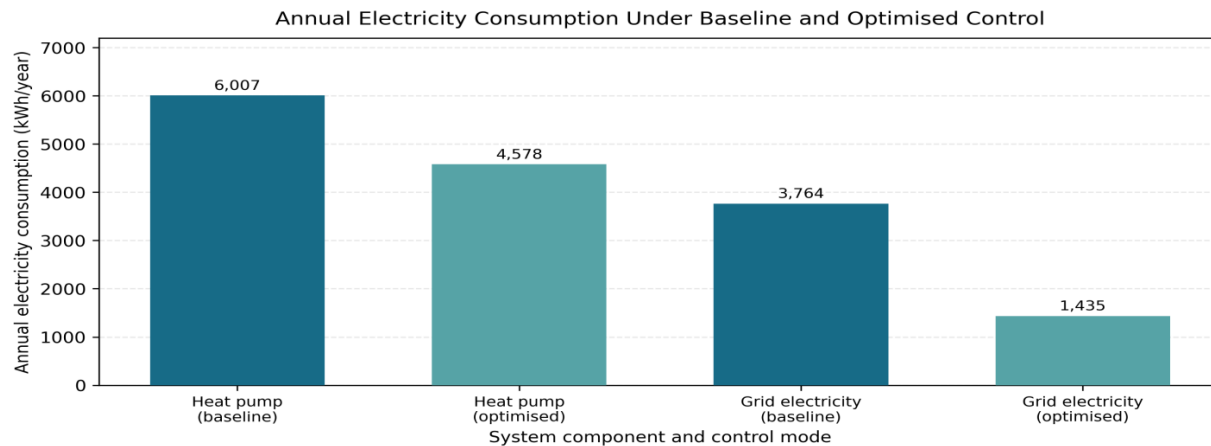


Figure 2. Comparison of Annual Electricity Consumption Under Baseline and Optimised Control.

The 23.8% reduction in heat pump electricity consumption is attributed to dynamic control across a wider comfort range, fewer part-load operating periods and greater use of heating and cooling hours that are favourable given the outdoor temperature. The 61.9% reduction in grid electricity results not only from lower consumption but also from shifting compressor operation to periods when solar generation is available. This second indicator should therefore not be equated with the heat pump's intrinsic energy efficiency; it reflects PV-load matching at the system level.

6. DISCUSSION

The estimated energy saving of 23.8% is physically consistent with the range reported in the international MPC literature, although direct comparisons should be made cautiously. A 2025 review of MPC implementations in real buildings reported average savings of approximately 30% in thermal energy and around 25% in electricity [6]. A 2026 systematic review of real-building studies found results ranging from a few per cent to 56.3% [7]. Performance therefore depends

substantially on building type, baseline control, weather, forecast accuracy and comfort constraints.

Three climate factors are particularly relevant to control under Fergana conditions. First, solar irradiation reaches 7.3–8.0 kWh/m²·day from June to August, allowing PV-supported cooling demand to align with daytime generation. Second, when the mean winter temperature falls to 0–3 °C, the temperature lift of an air-source heat pump increases and its COP decreases; preheating during sunny hours can be useful during this period. Third, seasonal wind speeds of 1.5–3.2 m/s change the infiltration component, so a model that ignores wind may misestimate loads in winter and during transitional seasons.

The literature shows that MPC performance depends directly on weather and load forecasts [3–5]. A review of control strategies for heat pumps identifies rule-based control and MPC as key approaches for increasing energy flexibility [8]. Recent work on adaptive MPC for solar-assisted and multi-source heat pumps indicates that combining a physical model with machine-learning forecasts can provide an additional 12% energy saving and substantially reduce temperature fluctuations [9]. This supports

adding meteorological forecasts and machine-learning-based load forecasts to the model in a future study for Fergana.

7. Experimental Validation Procedure for the Model

In an experimental test rig, outdoor air temperature, global solar irradiance, wind speed, indoor temperature, heat pump electrical power, supply and return water temperatures, and mass flow rate should be measured. Useful thermal power is calculated as follows:

$$Q_{HP} = \dot{m}_w c_{p,w} (T_{sup} - T_{ret}).$$

Agreement between the model and experiment is assessed using the root mean square error (RMSE) and mean absolute percentage error (MAPE):

$$RMSE = \sqrt{\frac{1}{N} \sum_{k=1}^N (y_k^m - y_k^s)^2},$$

$$MAPE = \frac{100}{N} \sum_{k=1}^N \left| \frac{y_k^m - y_k^s}{y_k^m} \right|.$$

Validation should be performed separately under cold and relatively cloudy winter conditions, spring transitional conditions, and hot and sunny summer conditions. Model parameters should be estimated using calibration data, while an independent period should be reserved for validation.

8. CONCLUSIONS

A climate-adapted mathematical model for model predictive control of a building heating and cooling system integrating solar energy and a reversible heat pump was developed for the

conditions of Fergana Region. The model treats outdoor air temperature, solar irradiance and wind speed as forecast disturbances. Wind-driven infiltration affects the building heat load; solar irradiance affects PV generation and passive gains; and outdoor temperature affects the COP and EER. For the selected 150 m² building, optimised control reduced annual heat pump electricity consumption by 23.8%. Aligning operation with PV generation further reduced electricity drawn from the grid.

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